MEMS beam steering for high power fibre lasers.

G. Brown, G. Thursby, W. Johnstone, D. Uttamchandani

The Centre for Microsystems and Photonics
University of Strathclyde
Glasgow, G1 1XW

Abstract

Compact, low operating power optical scanners using MEMS technology have been practically demonstrated. The scanners are capable of deflecting high power IR laser radiation generated from Er fibre lasers.

Keywords: micro-scanner, MEMS, fibre laser, dielectric coatings

Introduction

High-power fibre lasers have a number of merits as regards military applications: a) the ability to produce high power without the need for water-cooling; b) high overall efficiency; c) unsurpassed, near diffraction limited beam quality ($M^2 \approx 1$); and d) operation at eye-safe wavelengths. These features will drive the development of fibre lasers for military remote sensing applications by providing, from non-water-cooled systems, higher optical intensity at longer distances compared to existing commercial sources. Typical applications of CW high-power fibre lasers in the remote sensing arena include remote vibrometry and velocimetry, active imaging, target illumination, wind shear sensing and the interrogation of remote sensing devices, such as those falling under the concept of “smart dust”.

These applications require beam steering/scanning of the high-power fibre laser beams. However, at present, commercially available fibre laser systems do not offer an integrated, compact, high-power beam steering capability. The available option for beam scanning is to use off-the-shelf electro-mechanical scanning platforms (the actuators) to which are fixed high-power handling reflective optics, such as dielectric coated mirrors. This hybrid arrangement has the disadvantages of high weight, large volume and high operating power requirements. MEMS technology can produce miniature optical scanners where both the actuators and the reflectors are integrated into a single, compact, low-electrical-power unit dimensionally compatible with the beam diameter from a fibre laser.

However, before MEMS scanners can be used with any high-power lasers, they must be designed to withstand any potential damage which could arise from the incidence of the high-power beams on the relatively thin (< 25μm) reflecting mirrors of the scanners. The development of MEMS scanners for high-power laser sources, with a view to practical demonstration of such devices with a high-power (5W CW) erbium doped fibre laser at the eye-safe wavelength of 1550nm, is the principal aim of our research. The benefits are the implementation of high-power beam-scanned laser systems of reduced size and weight using scanners of ultra-low power consumption – these are

the desirable features of portable military equipment. The utilization of MEMS scanners also has an economic advantage since they can be produced at a significantly lower manufacturing cost compared to conventional bulk scanners.

A precursor DTC project, undertaken by Strathclyde University in 2005, established that static MEMS mirrors fabricated by a silicon-on-insulator (SOI) foundry process (SOIMUMPS) from MEMSCAP [1] and coated with gold or a custom dielectric multilayer stack were capable of withstanding high laser irradiation [2]. The mirrors were subject to 1 W CW at 1550 nm wavelength incident on a circular area with radius 100 μm for several hours with no apparent damage. The aim of the work reported here is to demonstrate a scanning mirror that can withstand similarly high levels of laser irradiation.

Modelling and Design

The basic design of the scanner is shown in Figure 1. A mirror platform forms part of a slender suspension beam that can tilt about the axis of the suspension beam. To create a tilting action of the mirror requires an out-of-plane force to be applied to the structure. Often, electrostatically-driven tilting mirrors are driven by applying an electrical potential between the mirror and an array of electrodes located below the mirror. This technique is not suitable for the proposed fabrication process because the SOI structure is relatively thick (compared to surface micromachined MEMS) and thus stiff, requiring a high field to achieve actuation. In addition, the actuating electrodes would be separated from the structural layer of the device by the thickness of the handle wafer (100s μm), further increasing the voltage required to achieve actuation.

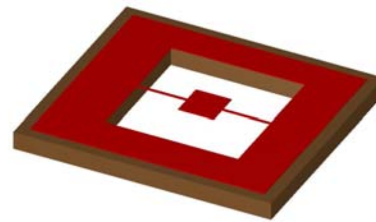

Figure 1 *Simplified layout of SOI MEMS torsional scanner*

The actuation method employed in this project is a vertically-offset comb-drive. The SOI process produces devices that are essentially planar but by applying a layer of gold (available as a step in the fabrication process) to one set of each pair of comb drives, the stress of the metal layer causes the fingers of the comb to bend upwards out of the plane. Thus when a voltage is applied between the fixed and suspended comb the attractive force between them has a vertical and horizontal component.

The arrangement of the vertically-offset comb drives in a fabricated device is shown in Figure 2. The combs are attached to the suspension beam in order to maximise the angle through which the mirror can be tilted.

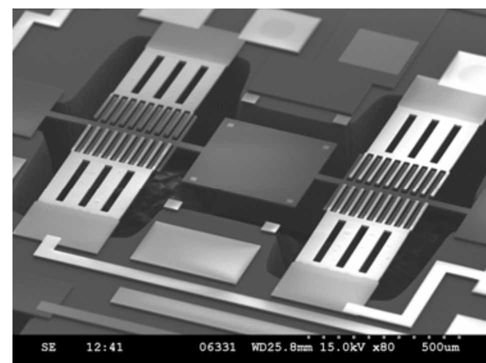

Figure 2 *SEM image of SOI MEMS torsional scanner showing arrangement of comb drives.*

The scanning mirror devices were modelled by finite element analysis (FEA) techniques using ANSYS, an FEA software package. A simplified 3d model of a device (consisting of only the components free to move, ie the mirror and suspension) was prepared in the MEMSPRO L-Edit layout editor, using process templates supplied by MEMSCAP for their multi-user SOI process (SOIMUMPS). The model was imported into ANSYS and a modal analysis carried out in order to identity the mechanical resonant modes of the structures. The principal mode of interest for a scanner application is the second mode, an oscillation about the axis of the suspension beam. The mode frequencies were calculated for a variety of device dimensions. A subset of these devices was chosen for fabrication, with the released structures 10 μm thick, and mirror platform 400 x 400 μm and the suspension beam varying in length from 1000 to 2000 μm and in width from 20 to 40 μm.

Pre-coat testing

Following fabrication at the silicon MEMS foundry, static testing of the scanners was undertaken. The flatness of the mirror components was assessed by carrying out surface profilometry using white light interferometry. The profile of the mirror in a test structure is shown in Fig 3. All the devices had the same mirror dimensions so this result is typical. The curvature of the mirror differs in the axes parallel to and orthogonal to the suspension beam. Along the axis of the suspension beam the edge of the mirror was raised 0.25 μm above the centre of the mirror. In the orthogonal axis the edge was 0.31 μm higher than the centre.

Dynamic testing was also undertaken to verify that the scanners operated in the desired mode. With a drive voltage of up to 50 V AC (peak-to-peak) combined with a DC offset chosen so that the voltage is unipolar the devices were examined with a microscope-coupled laser vibrometer. By varying the drive frequency and monitoring the output of the vibrometer the modal vibration frequencies of the devices could thus be identified. By examining the phase relationship between driving voltage and the displacement at various points on the device the mode type could be identified.

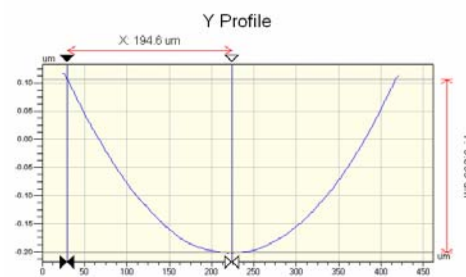

Figure 3 *Profile of mirror platform through midpoint in direction perpendicular to suspension.*

For its accurate operation, the vibrometer requires a sufficient amount of light from its laser to be reflected back from the device under test into the microscope. At high drive voltages around the mode frequencies, the angular tilt of the mirror became so large that this condition was not met (>~3^0). Consequently, the experimental set-up shown in Figure 4 was established to facilitate testing in this regime. A low power visible laser was used so that the extent of the scanned laser beam could be measured on the screen. The mirror tilt angle from rest could be deduced by simple trigonometry from the length of the scanned line on the screen and the distance from the mirror to the screen. The mirrors were observed to tilt in both directions about the tilt axis. Results from testing a device whose suspension beam has length 1750 μm and width 30 μm are shown in Figure 5. The device was driven at its scanning mode resonant frequency of 19.6 kHz and could scan a laser beam over a field of view of 50^0 (= 4 x mirror tilt from rest).

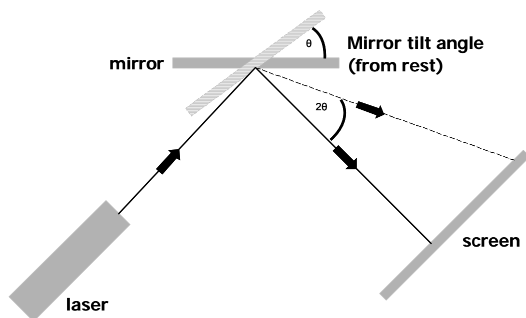

Figure 4 *Experimental set-up for measuring large tilt angles of mircromirrors.*

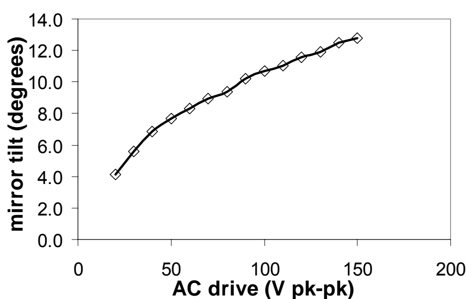

Figure 5 *Mirror tilt angles of a scanning micromirror as function of AC drive.*

Optical coating and post-coat testing

Dies from the same batch subjected to the pre-coat testing described above were coated with 8 pairs of SiO_2/Nb_2O_5 by an external contractor using magnetron sputtering. The coating was specified to have >99% reflectivity at 45^0 incidence for both s and p polarisations at a centre wavelength of 1550 nm. Optical profiling of the scanning micro mirrors showed that the stress of the coating caused a change in the sign and a marked alteration in the magnitude of curvature of the devices (see Figure 6). Along the axis of the suspension beam the edge of the mirror was 3.7 µm below the centre of the mirror. In the orthogonal axis the edge was 4.0 µm lower than the centre.

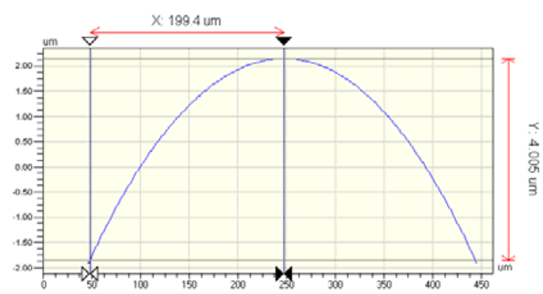

Figure 6 *Profile of dielectric coated mirror platform through midpoint in direction perpendicular to suspension.*

High power optical testing of the coated devices was carried out by directing the output of an Er fibre laser on to a micromirror via a cleaved monomode fibre positioned < 1mm above the mirror. The energy reflected from the mirror was measured and the reflectance of the film was found to be 99 ± 1 %, within the specification of the coating. Micromirrors were subject to 3.5 W of laser irradiation at 1550 nm for 3 hours with no significant change in the reflectance of the mirrors, and no change in the appearance of the mirror. The CW laser power density was calculated to be at least 125 MW m^{-2}.

The dynamic operation of MEMS scanners that had been coated with dielectric was investigated using the vibrometer and also the technique illustrated in Figure 4. All the devices tested were found to still operate in the scanning mode and mirror tilt angles of up to $\pm 10^0$ were obtained, similar to the values obtained before coating. Results from testing a set of devices whose dimensions are identical except for the width of the suspension beam are shown in Figure 7. The mode frequencies predicted by the FEA modelling are compared with the experimentally determined values for both uncoated and coated architectures. The values for modelled and measured frequencies of uncoated devices were found to agree well for the case of the out-

of-plane and orthogonal tilt modes (2nd order of the out-of-plane mode) but for the tilting mode, the measured frequency was only 75 % of the modelled value. It is thought that the discrepancy for the tilting mode may be due to inadequately dense FEA meshing through the depth of the structure.

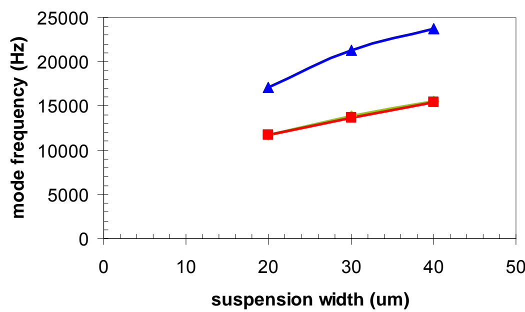

Figure 7a

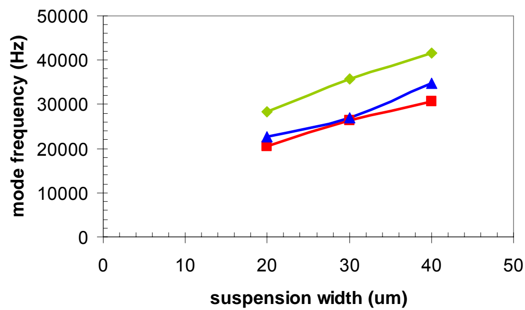

Figure 7b.

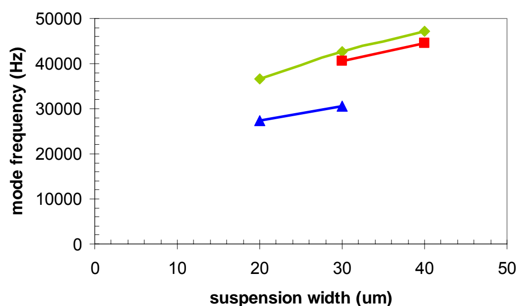

Figure 7c

calculated
measured - uncoated
measured - coated

Figure 7 *Vibrational mode frequencies for uncoated micromirrors (from modelling and experiment) and coated micromirrors. (a)1st mode(out-of-plane); (b) 2nd mode (scanner tilt mode); (c) 3rd mode (orthogonal scanner mode).*

Comparing the operation of coated and uncoated devices, the additional mass of coating might be expected to reduce vibration frequencies, but it appears that the added stress introduced by the coatings has had a more significant effect, leading to an increase in mode frequency for the first and third modes. The dielectric coatings were not included in the FEA modelling: no definitive data on Young's modulus or Poissons's ratio for the coating materials was available and a wide range of values is quoted in the literature.

Conclusions

MEMS scanners fabricated in 10 μm thick SOI have successfully been demonstrated achieving mirror tilt angles of up to 12^0. The scanning action was unaffected by the deposition of a dielectric multilayer. Scanners were able to withstand CW laser irradiation at levels of 125 MW m^{-2} for several hours with no damage sustained.

References

1. www.memscap.com
2. L Li, W Johnstone, D Uttamchandani, Paper B29, 3rd EMRS DTC Technical Conference, Edinburgh, 2006

Acknowledgements

The work reported in this paper was funded by the Electro-Magnetic Remote Sensing (EMRS) Defence Technology Centre, established by the UK Ministry of Defence and run by a consortium SELEX Sensors and Airborne Systems, Thales Defence, Roke Manor Research and Filtronic.